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FULL LENGTH ARTICLE

Source rock evaluation of some upper and lower Cretaceous sequences, West Beni Suef Concession, Western Desert, Egypt

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Abstract West Beni Suef Concession is located at the western part of Beni Suef Basin which is a relatively under-explored basin and lies about 150 km south of Cairo. The major goal of this study is to evaluate the source rock by using different techniques as Rock-Eval pyrolysis, Vitrinite reflectance (%Ro), and well log data of some Cretaceous sequences including Abu Roash (E, F and G members), Kharita and Betty formations. The BasinMod 1D program is used in this study to construct the burial history and calculate the levels of thermal maturity of the Fayoum-1X well based on calibration of measured %Ro and T_{max} against calculated %Ro model. The calculated Total Organic Carbon (TOC) content from well log data compared with the measured TOC from the Rock-Eval pyrolysis in Fayoum-1X well is shown to match against the shale source rock but gives high values against the limestone source rock. For that, a new model is derived from well log data to calculate accurately the TOC content against the limestone source rock in the study area. The organic matter existing in Abu Roash (F member) is fair to excellent and capable of generating a significant amount of hydrocarbons (oil prone) produced from (mixed type I/II) kerogen. The generation potential of kerogen in Abu Roash (E and G members) and Betty formations is ranging from poor to fair, and generating hydrocarbons of oil and gas prone (mixed type II/III) kerogen. Eventually, kerogen (type III) of Kharita Formation has poor to very good generation potential and mainly produces gas. Thermal maturation of the measured %Ro, calculated %Ro model, T_{max}

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and Production index (PI) indicates that Abu Roash (F member) exciting in the onset of oil generation, whereas Abu Roash (E and G members), Kharita and Betty formations entered the peak of oil generation.

1. Introduction

The Beni Suef Basin lies in N. Central Egypt and is surrounded by several fields (W. Rayan, Qarun, Karama) and Abu El-Gharadig Basin (Fig. 1) [33]. The study area (West Beni Suef Concession) is a western part of Beni Suef Basin which is a relatively under-explored basin and lies about 150 km south of Cairo and bisects the present day Nile Valley [33]. The Seagull Energy Corporation discovered the Beni Suef Oil Field in September 1997 and after that Qarun Petroleum Company discovered five oil fields (Azhar, Yusif, Gharibon, Lahun and Sobha) [33]. The Qarun Petroleum Company drilled the deepest exploratory well (Fayoum-1X) in 1991 which was plugged and abandoned as a dry hole (Fig. 2). This well reached to the basement with a total depth of 3492.37 m. This study concentrates on the source rock evaluation using Rock-Eval pyrolysis, %Ro, and well log data of Abu Roash (E, F and G members), Kharita and Betty formations for Fayoum-1X well. The Rock-Eval pyrolysis data are used to measure the TOC content, types of hydrocarbons from the relationship between the Hydrogen index (HI) and the Oxygen index (OI) [3]. The percentages of each type in the mixed kerogen are determined from the relationship between HI and T_{max} [19]. Thermal maturation is determined from the relationship between PI, T_{max} and measured %Ro with depth (m). The burial history model with calculated %Ro model is used to determine the levels of thermal maturation of the Fayoum-1X well. Well log data [gamma ray, density, neutron, deep resistivity (ILD), photoelectric factor (PEF) and sonic logs] are used to calculate the TOC content of the source rocks using the Density log method [24], $\Delta \log R$ technique [17], and a new derivative model for this study area depending on ILD, PEF and percentage of shale (V_{sh}) for Abu Roash (F member) only.

2. Lithostratigraphy

The stratigraphic column of the Beni Suef Basin (Fig. 3) represents a part of the Northern Western Desert which extends from the Pre-Cambrian granitic basement through the Jurassic clastics of Eghi Formation followed by the Cretaceous sequence which represents the main stratigraphic column of the study area and up to the Eocene Apollonia carbonates and Oligocene shales of the Dabaa Formation [33]. Late Tertiary to recent deposition is also recorded within the ancestral Nile valley and along its margins [33]. The Cretaceous sequence is divided into lower units made up primarily of clastics and the upper units made up mainly of carbonates [6]. The Lower Cretaceous sequence is divided into five rock units from bottom to top: Betty, Alam El-Bueib, Alamein, Dahab and Kharita formations, but Alamein Formation may be not deposited or eroded in the study area (Fig. 3). Betty Formation consists of a shale bed with sandstone interbeds. Alam El Bueib Formation is represented by a sandstone unit with frequent shale interbeds. Dahab Formation is a shale unit with thin interbeds of siltstone and sandstone. Kharita Formation consists of a fine to course grained sandstone with subordinate

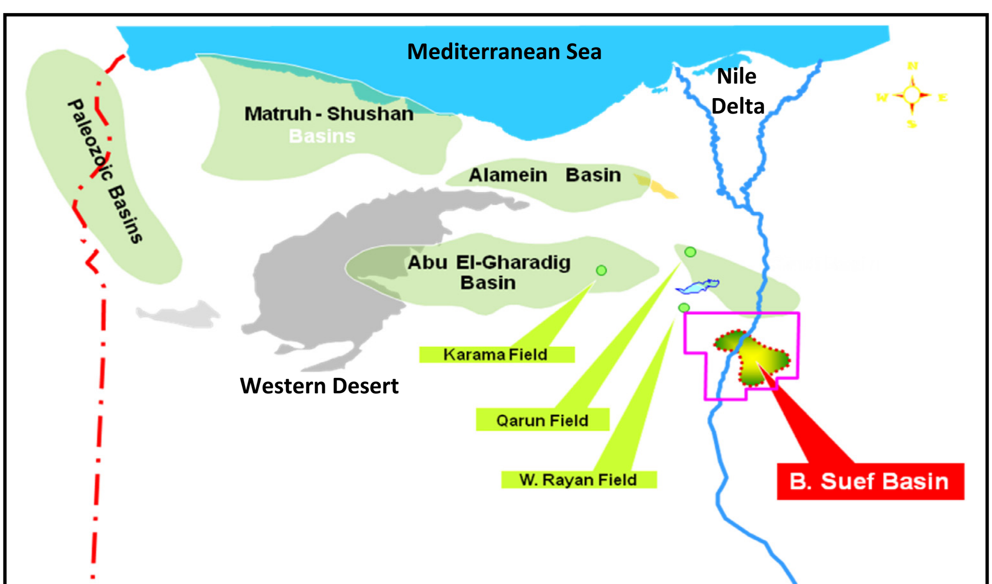

Figure 1 Basins and fields distribution map surrounding the Beni Suef Basin in the Western Desert, Egypt modified after [33].

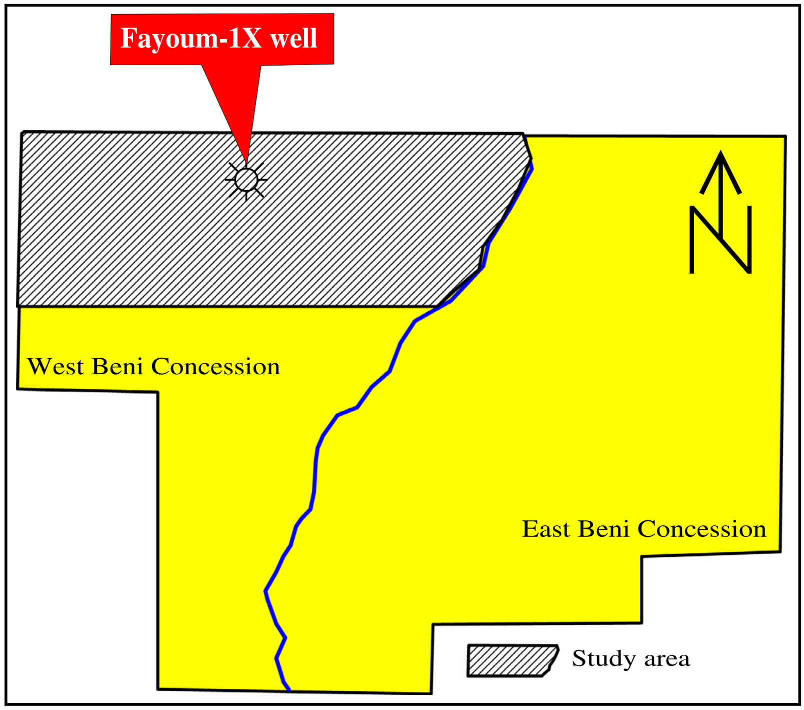

Figure 2 Base map of the study area (West Beni Suef Concession) including the studied well.

shale and carbonate beds. The Upper Cretaceous marks the beginning of a major transgression which resulted in the deposition of a dominantly carbonate section [21]. The Upper Cretaceous sequence is divided into three rock units from bottom to top: Baharyia, Abu Roash and Khoman [6] (Fig. 3). The Baharyia Formation comprises medium- to coarse-grained sandstone with calcareous silty shale interbeds. Abu Roash Formation is divided into seven members designated from bottom to top: G, F, E, D, C, B and A [21]. Members B, D, and F are relatively clean carbonates whereas members A, C, E and G are largely fine clastics with minor carbonate interbeds. The Khoman Formation consists of chalky limestone which is deposited in open marine outer shelf conditions.

3. Materials and methods

According to the Pennzoil Company, ditch samples from Fayoum-1X well were analyzed by the StratoChem Services (SCS) Company to determine the Rock-Eval pyrolysis and %Ro analysis. This study depends on geochemical data (Rock-Eval pyrolysis and %Ro) and well log data (Gamma ray, Density, Neutron, ILD, PEF and Sonic logs) obtained from the Qarun Petroleum Company of Abu Roash (E, F and G members), Kharita and Betty formations in Fayoum-1X well.

3.1. Rock-Eval pyrolysis data

Rock-Eval pyrolysis data give information on the quantity, type and thermal maturity of the organic matter. Pyrolysis is a widely used degradation technique that allows breaking a complex subsidence into fragments by heating it under an inert atmosphere [18]. Rock-Eval is expressed in mg/g of rock and includes four basic parameters ($S1$, $S2$, $S3$ and T_{max}). $S1$ represents the quantity of free hydrocarbons present in the rock and is roughly analogous to the solvent extractable portion of the organic matter. $S2$ represents the quantity of hydrocarbons released by the kerogen in the sample during pyrolysis. $S3$ represents the amount of oxygen present in kerogen. T_{max} is the temperature at which the maximum rate of generation (of the $S2$ peak) occurs and can be used as an estimate of thermal maturity.

3.2. Vitrinite Reflectance (%Ro) data

Today, %Ro is the most widely used indicator for identifying thermal maturation of sedimentary organic matter, because it extends over a longer maturity range than any other indicator. %Ro is used as a technique for determining the maturation of the organic matter present in sedimentary rocks was first described by [31].

3.3. Well log data

Many techniques proposed to use the well log in the determination of the amount of TOC in the source rock. In the present study the TOC is estimated using three different methods. The first ($\Delta \log R$ technique) is proposed by Passey et al. [17]. This method depends mainly on the combination of resistivity with porosity logs and allows organic richness to be accurately assessed in a wide variety of lithologies and maturities using common well logs. The second method of Schmoker and Hester [24] relates the TOC to the density log only. This method can be successfully applied, if the constants A and B are calibrated and matched with the available analytical geochemical

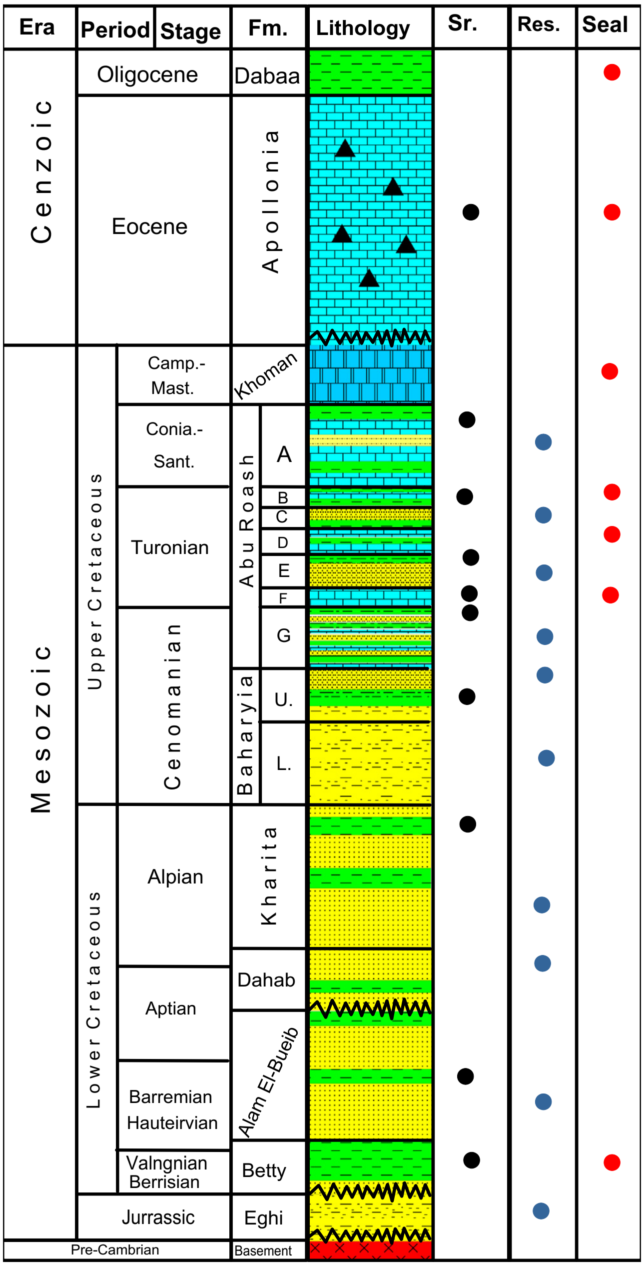

Figure 3 Subsurface geologic column of the Beni Suef Basin modified after [33].

data, if found. The third method which is derived during this study relates to PEF, ILD and V_{sh} logs.

3.3.1. ΔLog R technique

Passey et al. [17] developed a technique used for both carbonates and clastics using sonic-resistivity overlay. They also introduced the term "Δlog *R*" which is linearly related to TOC and is a function of maturity. In this technique, sonic travel time "Δt" and true formation resistivity "R_t" were scaled so as to get a ratio of 164 μs/m to one resistivity cycle. The separation between two curves (Δt to left and R_t to right) defined Δlog *R* that can be calculated from the following equation:

$$\Delta \log R_{\text{Sonic}} = \log_{10}(R/R_{\text{baseline}}) + 0.02 \times (\Delta t - \Delta t_{\text{baseline}}) \quad (1)$$

Then, the TOC is calculated using the following relation:

$$\text{TOC1} = (\Delta \log R) \times 10^{(2.297 - 0.1688 \times \text{LOM})} \quad (2)$$

where LOM is the level of maturity, 6–7 for onset of maturity for oil prone kerogen and 12 corresponds to the onset of over maturity for oil-prone kerogen.

3.3.2. Density log method

The TOC content generally reflects the total amount of organic matter preserved with sediment after digenesis and metamorphism. The TOC (wt.%) can be estimated by the Schmoker and Hester [24] equation:

$$\text{TOC2(wt.\%)} = (A/\rho) - B \quad (3)$$

where the two constants A and B are calculated from the linear relationship between the laboratory determined TOC wt.% and the bulk density. We used $A = 10$ and $B = 2.8$ for Abu Roash (E, F and G members), Kharita and Betty formations.

3.3.3. A new model derived for the study area

A new model depends mainly on the combination of PEF, GR and ILD logs and allows TOC to be accurately assessed in a wide variety of lithologies. Sandstones have low PEF, while limestones have high PEF [23]. Clays, heavy minerals and iron-bearing minerals have high PEF. Thus, the log is very useful for determining mineralogy. That ILD log readings increase dramatically in mature source rocks is an important observation, and is presumably related to the generation of nonconducting hydrocarbons [16,13,25]. Gamma ray method represents one of the best indicators estimating shale volume in reservoirs free of radioactive materials other than those found in shales. Calculation of the gamma ray index is the first step needed to determine the volume of shale from a gamma ray log [22].

$$I_{GR} = \frac{GR_{\text{log}} - GR_{\text{min}}}{GR_{\text{max}} - GR_{\text{min}}} \quad (4)$$

There is no scientific basis for assuming that the relationship between gamma ray value and shale volume should be linear. Thus a modification has been proposed by [1]. For calculation of shale volume from the gamma ray index, the modification changes between younger (unconsolidated) rocks and older (consolidated) rocks as follows: For Pre-Tertiary, older consolidated rocks

$$V_{\text{sh}} = 0.33[2^{\langle 2 \times I_{GR} \rangle} - 1.0] \quad (5)$$

In this study, a new model is derived depending on the PEF, ILD logs and the V_{sh} as follows:

Table 1 Organic carbon richness based on TOC and Rock-Eval pyrolysis data [18].

Quality	TOC (wt.%)	*S*1 (mg. Hc./gm rock)	*S*2 (mg. Hc./gm rock)
Poor	0 to < 0.5	0–0.5	0–2.5
Fair	0.5–1.0	0.5–1.0	2.5–5
Good	1–2	1–2	5–10
Very good	> 2	> 2	> 10

Table 2 Rock-Eval pyrolysis and TOC data of the Fayoum-1X well.

Formation Name	Depth (m)	TOC (wt.%)	$S1$ (mg/g)	$S2$ (mg/g)	$S3$ (mg/g)	(BI) $S1$/TOC	T_{max} degC	(HI) $S2$/TOC	(OI) $S3$/TOC	PI $S1/(S1 + S2)$	$S1 + S2$ (mg/g)
Abu Roash (E member)	1535.67	2.23	0.4	4.36	1.47	0.18	430	196	66	0.08	4.76
	1541.77	0.84	0.13	1.33	0.59	0.15	433	158	70	0.09	1.46
	1553.97	1.12	0.09	1.58	0.42	0.08	432	141	38	0.05	1.67
	1557.01	1.51	0.12	2.35	0.46	0.08	433	156	30	0.05	2.47
	1560.06	2.62	0.2	3.76	0.64	0.08	432	144	24	0.05	3.96
	1563.11	1	0.12	1.15	0.84	0.12	431	115	84	0.09	1.27
	1566.16	1.08	0.06	1.18	0.85	0.06	432	109	79	0.05	1.24
	1572.26	0.8	0.09	0.79	1.09	0.11	430	99	136	0.1	0.88
	1587.5	0.51	0.06	0.53	0.66	0.12	400	104	129	0.1	0.59
	1614.94	0.59	0.08	0.59	0.51	0.14	353	100	86	0.12	0.67
	1627.14	0.61	0.14	0.83	0.95	0.23	371	136	156	0.14	0.97
	1645.43	0.72	0.13	0.85	0.72	0.18	431	118	100	0.13	0.98
	1669.82	0.92	0.13	1.1	0.69	0.14	431	120	75	0.11	1.23
	1672.87	1.15	0.12	1.52	0.37	0.10	432	132	32	0.07	1.64
	1678.97	1.19	0.09	0.75	0.77	0.08	431	63	65	0.11	0.84
	1688.11	3.66	0.26	5.94	0.69	0.07	428	162	19	0.04	6.2
	1691.16	1.56	0.1	1.53	0.95	0.06	441	98	61	0.06	1.63
	1709.45	0.51	0.04	0.31	0.7	0.08	333	61	137	0.11	0.35
Abu Roash (F member)	1749.09	1.52	0.37	5.83	0.39	0.24	426	384	26	0.06	6.2
	1752.14	1.27	0.26	3.88	0.35	0.20	427	306	28	0.06	4.14
	1770.43	4.46	2.19	39.01	0.84	0.49	422	875	19	0.05	41.2
	1779.58	3.42	1.99	20	0.7	0.58	425	585	23	0.08	21.99
	1788.73	2.93	1.3	22.12	0.84	0.44	423	755	29	0.06	23.42
Abu Roash (G member)	1800.92	1.08	0.16	2.71	0.7	0.15	425	251	65	0.06	2.87
	1810.06	0.63	0.09	0.59	0.75	0.14	427	94	119	0.13	0.68
	1919.82	0.51	0.05	0.27	0.3	0.10	428	53	59	0.16	0.32
	1983.84	0.84	0.15	1.55	0.43	0.18	435	185	51	0.09	1.7
	1992.99	1.15	0.12	2.33	0.29	0.10	437	203	25	0.05	2.45
Kharita	2337.5	1.12	0.25	1.7	0.47	0.22	435	152	42	0.13	1.95
	2386.28	0.8	0.22	1.06	1.13	0.28	435	133	141	0.17	1.28
	2395.43	0.8	0.19	1.03	0.69	0.24	433	129	86	0.16	1.22
	2441.16	0.58	0.13	0.68	0.25	0.22	368	117	43	0.16	0.81
Betty	3087.5	0.65	0.28	1.17	0.35	0.43	437	180	54	0.19	1.45
	3090.55	1.16	0.42	2.26	0.32	0.36	441	195	28	0.16	2.68
	3093.6	1.12	0.46	2.48	0.33	0.41	442	221	29	0.16	2.94
	3099.7	1.08	0.54	2.64	0.31	0.50	440	244	29	0.17	3.18
	3114.94	0.57	0.21	0.99	0.25	0.37	439	174	44	0.18	1.2
	3117.99	0.62	0.25	1.08	0.3	0.40	438	174	48	0.19	1.33

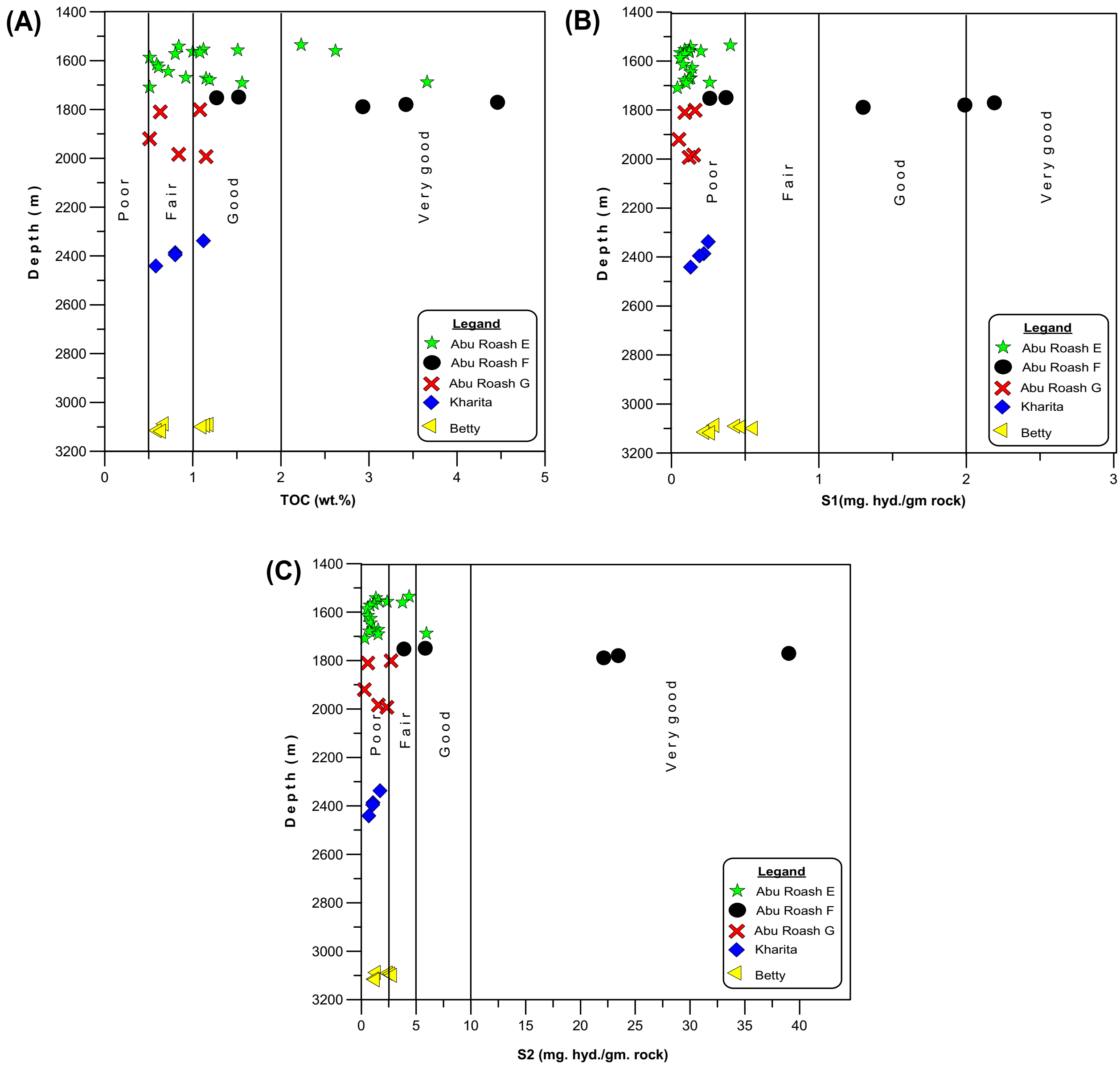

Figure 4 Organic carbon richness from relationships between: (A) TOC vs. Depth, (B) S1 vs. Depth and (C) S2 vs. Depth of Abu Roash (E–G members), Kharita and Betty formations in the Fayoum-1X well.

$$\mathrm{TOC3} = \mathrm{ABS}[-6.906 + (3.186 \times \mathrm{Log}(\mathrm{PEF}) + 0.487 \times \mathrm{Log}(\mathrm{ILD}))] - 6 \times V_{sh} \quad (6)$$

3.4. Basin modeling

To assess the maturation history of potential source rocks, BasinMod 1D® (Platte River Associates, Inc.) is used for this study to calculate the levels of thermal maturity of the Fayoum-1X well based on the calibration of measured %Ro and T_{max} against the Lawrence Livermore National Laboratory (LLNL) Easy %Ro model [30]. Basin modeling has been successfully applied to some important petroliferous basins in different locations, such as the Masila Basin in Yemen by [5], the Shoushan Basin in Egypt by Shalaby et al. [27] and the Matruh–Shushan Basin in Egypt by Metwalli and Pigott [14].

In this study, the burial history model of Fayoum-1X well is constructed using the LLNL Easy %Ro model, heat flow, stratigraphic thickness derived from the well composite logs, percentages of three lithological facies (sandstone, shale, and limestone), absolute ages, formation temperatures and erosional thickness base on seismic and well log data. Basin modeling simulations were performed using the forward modeling approach and input data from analogous wells of the study area.

4. Results and discussion

4.1. Organic carbon richness from Rock-Eval pyrolysis data

The organic carbon richness of the rock samples, as expressed by the weight percent of TOC content, is important

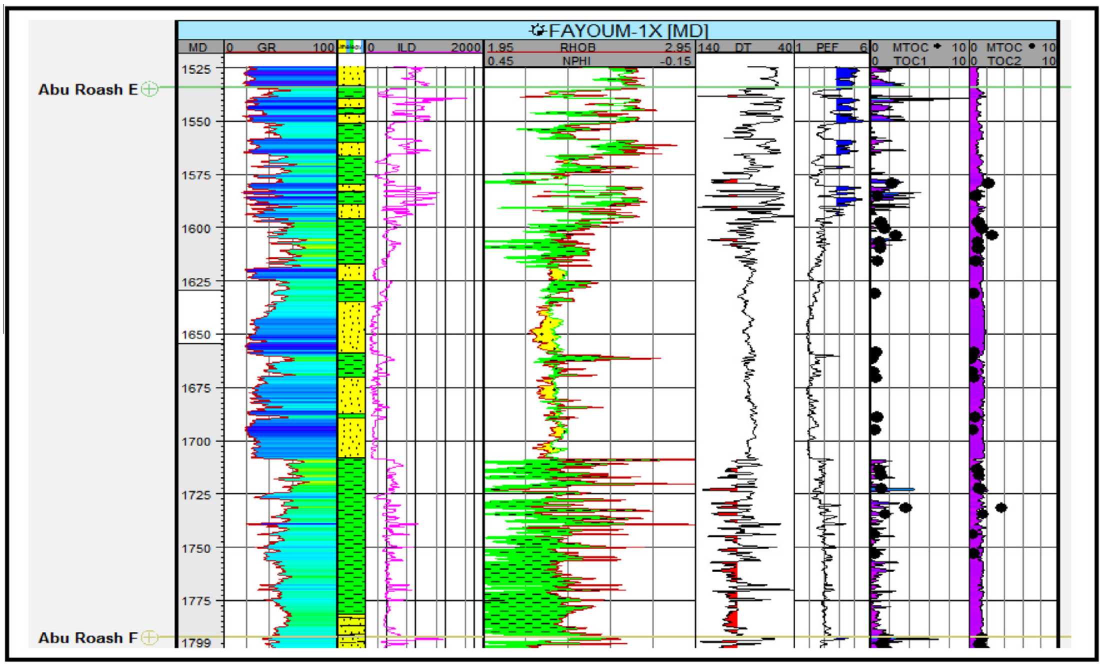

Figure 5 TOC calculations from different models: TOC1 ($\Delta \log R$ technique) and TOC2 (Density log method) of Abu Roash (E member) in the Fayoum-1X well.

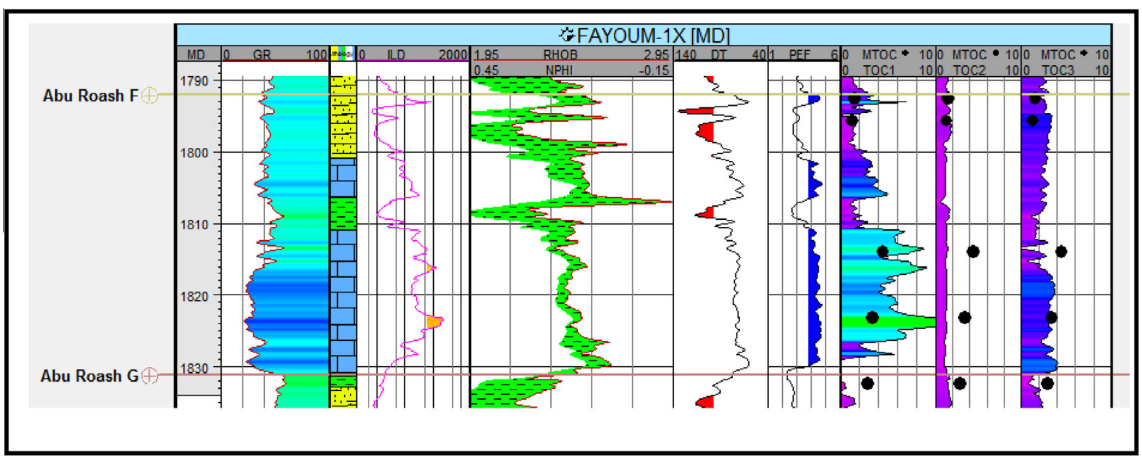

Figure 6 TOC calculations from different models: TOC1 ($\Delta \log R$ technique), TOC2 (Density log method), and TOC3 (derivative model) of Abu Roash (F member) in the Fayoum-1X well.

in the evaluation of sediments as a source of petroleum [32,18] presented a scale for the assessment of source rocks potentiality, based on the TOC and Rock-eval pyrolysis data ($S1$ and $S2$) (Table 1). Rock-Eval pyrolysis is used to determine the TOC content of Abu Roash (E, F and G members), Kharita and Betty formations of the Fayoum-1X well (Table 2).

Abu Roash (E member) is a fair to very good source rock with the TOC content ranging from 0.51 to 3.66 wt.% (Fig. 4A), whereas the Rock-Eval pyrolysis data ($S1$ and $S2$) indicate that Abu Roash (E member) is a mainly poor to fair source rock(Fig. 4B and C, respectively).

Abu Roash (F member) is a good to very good source rock with the TOC content ranging from 1.27 to 4.46 wt.% (Fig. 4A), whereas the Rock-Eval pyrolysis data ($S1$ and $S2$) reflect that Abu Roash (F member) is a very good source rock (Fig. 4B and C, respectively). Abu Roash (G member) is a fair to good source rock with the TOC content ranging from 0.51 to 1.15 wt.% (Fig. 4A), whereas the Rock-Eval pyrolysis data ($S1$ and $S2$) indicate that Abu Roash (G member) is a poor to fair source rock.

Kharita Formation is a fair to good source rock with the TOC content ranging from 0.58 to 1.16 wt.% (Fig. 4A), whereas the Rock-Eval pyrolysis data ($S1$ and $S2$) indicate that the Kharita Formation is a poor source rock (Fig. 4B and C, respectively). Betty Formation is a fair to good source rock with the TOC ranging from 0.39 to 1.16 wt.% (Fig. 4A), whereas the Rock-Eval pyrolysis data ($S1$ and $S2$) indicate that the Betty Formation is mainly a poor to fair source rock (Fig. 4B and C, respectively).

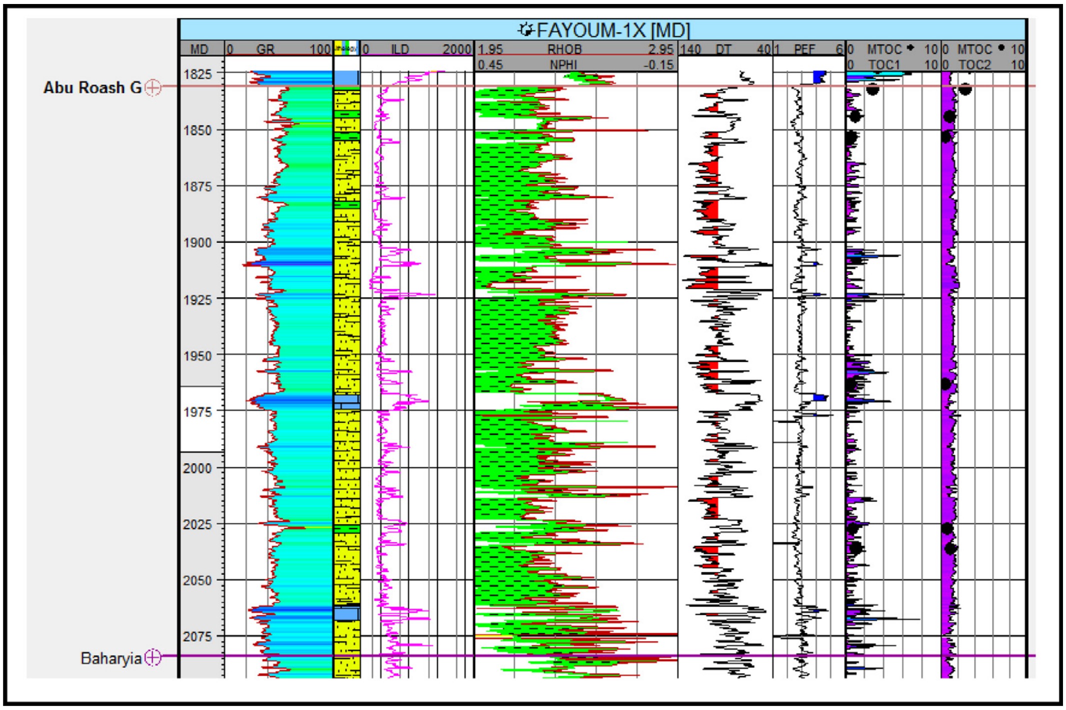

Figure 7 TOC calculations from different models TOC1 ($\Delta\log R$ technique) and TOC2 (Density log method) of Abu Roash (G) member in the Fayoum-1X well.

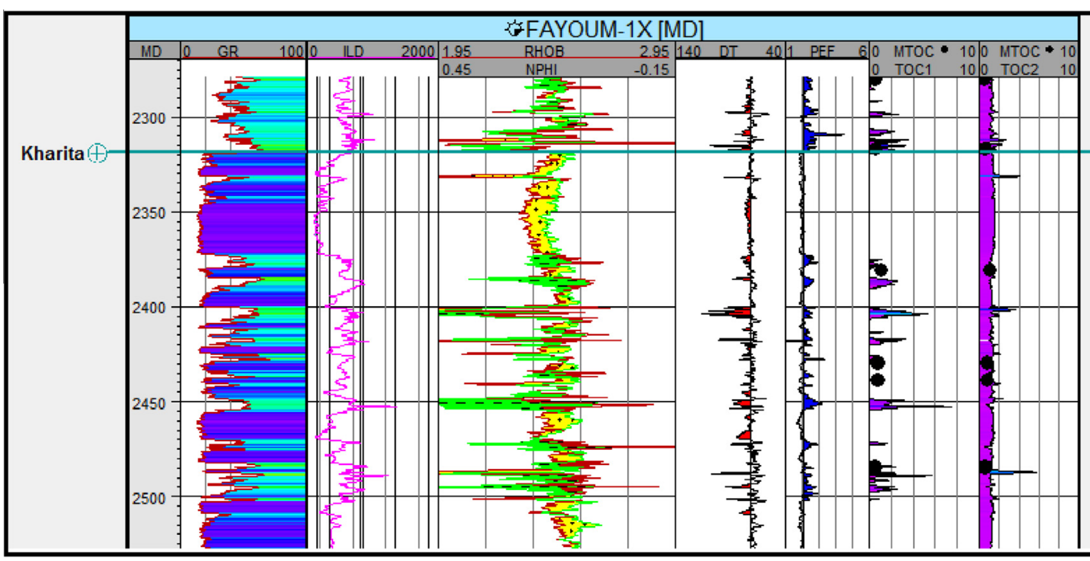

Figure 8 TOC calculations from different models TOC1 ($\Delta\log R$ technique) and TOC2 (Density log method) of the Kharita Formation in the Fayoum-1X well.

4.2. Organic carbon richness from well log data

Organic matter can be determined directly from laboratory analyses of the shale samples, but indirect methods based on wireline log data are used. The feasibility of interpreting organic matter from wireline measurements comes from its physical properties, which differ considerably from those of the mineral components of its host rock: lower density, slower sonic velocity or higher sonic transit time, frequently higher uranium content, higher resistivity and higher hydrogen and carbon concentrations. Consequently, the logs used for source rock evaluations most commonly include density, sonic, gamma ray, neutron and resistivity [26,7,12].

4.2.1. Well log response to source rock

The common utilized well logs to detect source rock are (Gamma ray, resistivity, density, neutron and sonic) logs. In the Gamma ray log, the presence of organic matter, which is

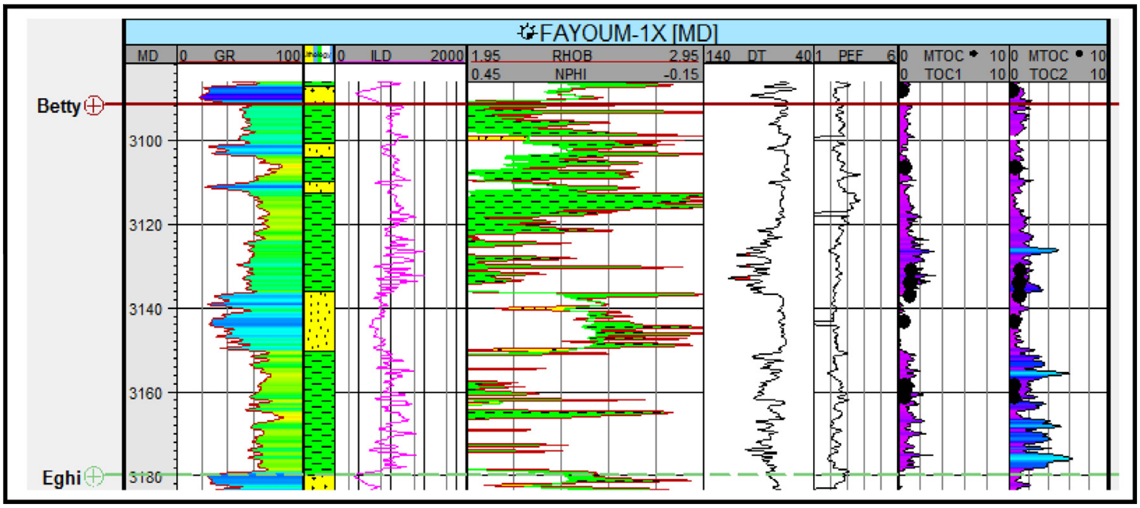

Figure 9 TOC calculations from different models: TOC1 ($\Delta \log R$ technique) and TOC2 (Density log method) of the Betty Formation in the Fayoum-1X well.

associated with uranium, resulted in an increase of GR readings. In the Resistivity log, when the source rock becomes mature, free oil is present in voids and fractures, and therefore, the resistivity of the source rock increases significantly by a factor of 10 or more [15]. In the Density log, non-source shale has a density matrix ranging from 2.67 to 2.72 g/cm^3 and the presence of organic matter will lower the rock density. Neutron log measures the hydrogen index and therefore, increasing of the neutron log reflects the presence of source rock. In the Sonic log, at the same condition of compaction, and lithology, two cases are observed. They are increasing of sonic travel time (Δt) in immature source rock and relative decreasing of (Δt) in the mature source rock.

4.2.2. Determination of TOC content

From the above discussion, the TOC content is calculated from $\Delta \log R$ technique, Density log method for Abu Roash (E and G members), Kharita and Betty formations but a new derivative model is used only for the Abu Roash (F) member in the Fayoum-1X well. Fig. 5 illustrates the TOC calculation from the above methods, the TOC values of the Abu Roash (E) member reached to 4 wt.% which indicates a very good source rock and the calculated TOC gives good matching with measured TOC against shale intervals in the case of $\Delta \log R$ technique and Density log.

In the Abu Roash (F member) (Fig. 6), the calculated TOC from $\Delta \log R$ technique ranges from 1 to 4 wt.%, whereas with the Density log method is very low than the measured TOC. Eventually, calculated TOC from the new model gives good matching with the measured TOC against limestone intervals. The calculated TOC indicates that Abu Roash (F) is a very good source rock.

The calculated TOC from $\Delta \log R$ technique and the Density log method gives good matching with the measured TOC against shale intervals, on the other hand gives high values against limestone in the case of the $\Delta \log R$ technique for Abu Roash (G member), Kharita and Betty formations (Figs. 7–9), respectively.

4.3. Types of organic matter

The type of organic matter completes the organic richness in evaluating the generating potential of a source rock [4]. The organic matter in potential source rocks must be of the type that is capable of generating petroleum. The HI refers to the remaining generation potential of organic matter and T_{max} represents the temperature at the peak of hydrocarbon generation. Both HI and T_{max} from Rock-Eval pyrolysis help to identify the quality and maturity of possible source rocks [18,9,2]. HI values and hydrocarbon generation potential, i.e., $S2$ of Rock-Eval pyrolysis are indicative of the quality of organic matter. HI values below 150 mg Hc/gm rock indicate the absence of a significant amount of oil-generative lipid materials and confirm the kerogen as mainly types III and IV. HI values above 150 mg Hc/gm rock reflect increasing amounts of lipid-rich materials (cutinite, resinite and exinite) or marine algal materials. Samples with HI values between 150 and 300 contain type-III kerogen higher than type-II and therefore, have marginal to fair potential for liquid hydrocarbons.

The type of organic matter is determined from the Rock-Eval pyrolysis data for Abu Roash (E, F and G members), Kharita and Betty formations of Fayoum-1X well. Abu Roash (F member) is represented by mainly oil prone of (mixed type I/II) kerogen (Fig. 10A). But Abu Roash (E and G members), Kharita and Betty formations represented oil and gas prone of (mixed type II/III) kerogen. The relationship between T_{max} and HI (Fig. 10B) indicates that the percentage of type II in the mixed type II/III kerogen reached to 25% (Abu Roash E member), 40% (Abu Roash G member), and 15% (Kharita Formation) and ranges from 20% to 40% (Betty Formation). Whereas in Abu Roash (F member) the percentage of type II reached to 60 in the mixed type I/II kerogen.

4.4. Thermal maturation

4.4.1. Thermal maturation from Rock-Eval pyrolysis data

The relationship between T_{max} and depth (Fig. 11A) and relationship between PI and depth (Fig. 11B) reflect that Abu

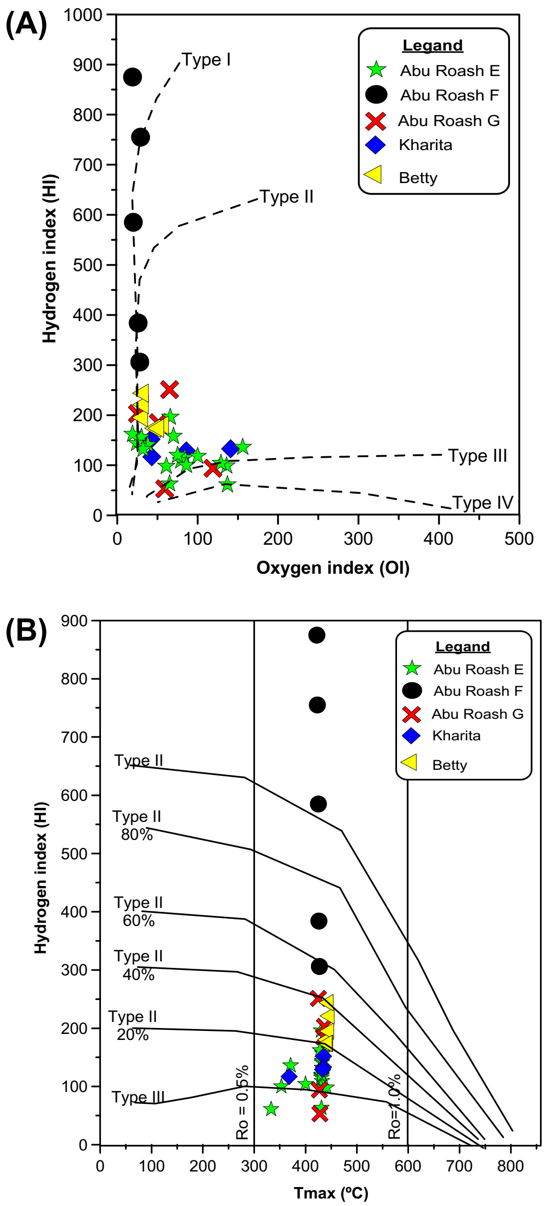

Figure 10 Relationship between OI and HI (A) and relationship between T_{max} and HI (B) to determine the type of organic matter of Abu Roash (E–G members), Kharita and Betty formations in Fayoum-1X well.

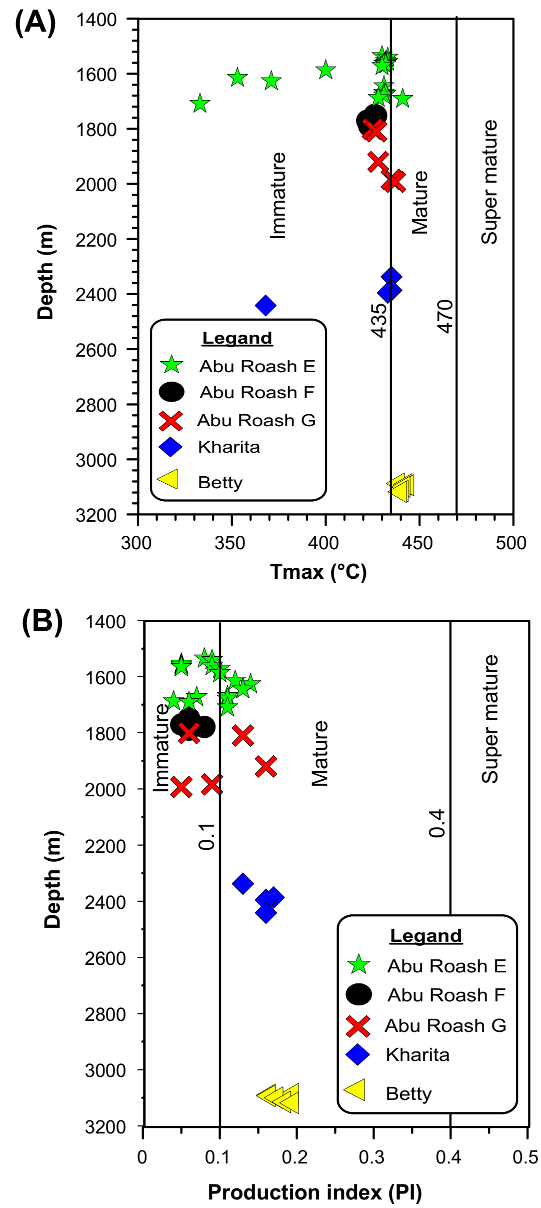

Figure 11 Relationship between T_{max} and Depth (A) and relationship between PI and Depth (B) to determine the thermal maturation of Abu Roash (E–G members), Kharita and Betty formations in the Fayoum-1X well.

Roash (F member) is present on the margin of maturation, whereas Abu Roash (E and G members) and Betty and Kharita formations range from immature to mature stages.

4.4.2. Thermal maturation from measured %Ro

[32] Detected at the onset, peak and end of oil generation for the different types of kerogen is based on %Ro (Table 3). The %Ro is used to determine the level of maturation for Abu Roash (E, F and G members), Kharita and Betty formations (Table 4) and (Fig. 12). In Abu Roash (E member) the %Ro values reached to 1.09, indicates the presence of mature source rock (Peak of generation). But in Abu Roash (F member), the maximum value of %Ro is 0.44, which reflects the presence of immature source rock. The maximum values of

Table 3 The oil generation for the different types of kerogen with %Ro [32].

Generation	Type I	Type II	Type III %Ro
Onset of oil generation	0.65	0.5	0.55
Peak of oil generation	1.1	0.8	0.9
End of oil generation	> 1.4	> 1.4	> 1.4

%Ro are 1.86, 1.36 and 1.8 for (Abu Roash G member), Kharita and Betty formations, respectively. These results mean that they reached to super mature stage (End of generation). The measured %Ro values do not increase gradually with depth

Table 4 Measured %Ro of the Fayoum-1X well.

Formation Name	Depth (m)	%Ro
Abu Roash (E member)	1532.63	0.56
	1535.67	1.09
	1642.38	0.68
	1645.43	0.68
	1685.06	0.65
	1688.12	0.99
Abu Roash (F member)	1767.38	0.38
	1770.43	0.38
	1785.67	0.44
	1788.73	0.44
Abu Roash (G member)	1916.77	0.65
	1919.82	1.86
Kharita	2334.45	0.73
	2392.38	0.68
	2395.43	1.36
Betty	3096.65	0.91
	3099.7	0.91
	3114.94	0.8
	3117.99	1.8

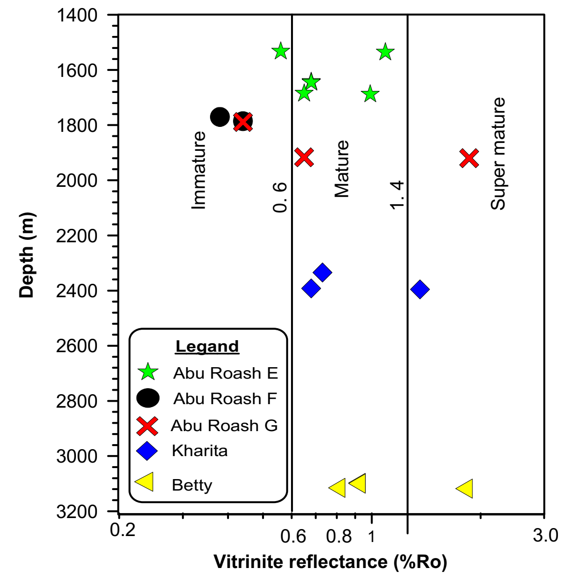

Figure 12 Thermal maturation from relationship between %Ro and depth of the Fayoum-1X well.

and is questionable for a few samples, due to limited number of measurements and/or the structure setting of the study area. Most deeper samples have two populations of vitrinite, which are difficult to identify as caving, indigenous or recycled.

4.4.3. Burial history model of Fayoum-1X well

All parameters and the input data to BasinMod software of the Fayoum-1X well are present in Table 5. The burial history model of Fayoum-1X well (Fig. 13) illustrates the relationship between depth subsurface (m) and Age (my) where the total depth reached to 3509.9 m at basement rocks and effect by more than erosion event. The 1st erosion event occurred between basement (Pre-Cambrian) and Eghi Formation (Jurassic age) due to tectonic uplifting and leads to missing all Paleozoic rock units and the Triassic age which reached to more than 300 m. The 2nd erosion event occurred between Eghi and Betty formations which reached to 200 m eroded thickness of the M. Jurassic age. The 3rd erosion event occurred between Alam El-Bueib and Dahab formations where the Alamein dolomite Formation is eroded or due to non deposition due to tectonic uplifting, where the eroded thickness reached to 100 m. The 4th erosion event that occurred between Khoman Formation (U. Cretaceous age) and Apollonia Formation (Eocene age) due to tectonic uplifting leads to missing more than 200 m thickness of the Paleocene age rock units. The last erosion event occurred at the top of Dabaa Formation of 400 m eroded thickness due to uplifting and weathering.

The burial history model of Fayoum-1X well with LLNL Easy %Ro maturity indicator (Fig. 13) reflects that Abu Roash (A–F and upper part of G members) reached to early mature stage (0.5–0.7 %Ro), whereas (the lower part of Abu Roash (G) member), Baharyia, Kharita, Dahab, Alam El-Bueib, Betty formations reached to mid mature stage (0.7–1 %Ro). The relationship between depth (m) and formation temperature (°C) of the Fayoum-1X well (Fig. 14) shows that the formation temperature increases with increasing the depth of burial and reached to 123.31 (°C) at the total depth of 3509.9 m at the basement rocks.

The calibration of measured %Ro and T_{max} against LLNL Easy %Ro model of the Fayoum-1X well (Figs. 15 and 16, respectively) to adjustment of the heat flow. This calibration gives a good match between them and shows that, the calculated Easy %Ro values of the Fayoum-1X well are correct and reliable.

4.5. Generation potential

According to [4], the source-rock-generating potential obtained from the diagram of Rock-Eval pyrolysis data ($S1 + S2$) and TOC are summarized in Fig. 17. The total generation potential ($S1 + S2$) of deep burial sediments is considered a poor source if it <2, 2–5 for fair, 5–10 for good and >10 for very good generating source [8]. Fig. 17 indicates that Abu Roash (F) member ranges from fair to excellent generation potential, whereas Abu Roash (E and G members), Kharita and Betty formations ranges from poor to fair generation potential (Fig. 17).

4.6. Expulsion potential

The maturity at which the Bituminous Index (BI) ($S1$/TOC) value begins to decline represents the start of an efficient oil window, or indicates efficient oil expulsion [19]. The highest BI is formed at a value of approximately within (0.7–0.8 %Ro) and within (0.9–1.1 %Ro), T_{max} within (438–450 °C T_{max}) and within (442–460 °C T_{max}) which is based on the type of organic matter [10]. The compounds generated in the early stages are presumed to be bitumen or heavy crude oil which later forms lighter oils by partial decomposition at higher maturity [11]. During maturity, $S2$ is continuously decomposing, causing a decrease in $S2$ and an increase in free hydrocarbon

Table 5 Input data used for burial and thermal history models of the Fayoum-1X well.

Formation or event	Type	Begin age (my)	Top depth (m)	Present thick. (m)	Eroded thick. (m)	Lithology	Lithology pattern
Erosion 5	E	6			−400		
Dabaa ghost layer	D	18			400	Shale	Shale
Dabaa	F	23.5	0	33.23		Shale	Shale
Apollonia	F	37	33.23	948.78		Limestone	Limestone
Erosion 4	E	65			−100		
Khoman ghost layer	D	68			100	Limestone	Limestone
Khoman	F	83	982.01	135.97		Limestone	Limestone
Abu Roash (A)	F	88	1117.98	76.23		Abu Roash (A)	Shaley sand
Abu Roash (B)	F	89	1194.21	168.59		Abu Roash (B)	Limestone
Abu Roash (C)	F	90	1362.8	50.9		Abu Roash (C)	Shaley sand
Abu Roash (D)	F	91	1413.7	77.15		Abu Roash (D)	Limestone
Abu Roash (E)	F	92	1490.85	257.62		Abu Roash (E)	Shaley sand
Abu Roash (F)	F	92.5	1748.47	39.03		Abu Roash (F)	Limestone
Abu Roash (G)	F	93.5	1787.5	253		Abu Roash (G)	Sandy shale
Baharyia	F	99.5	2040.5	234.5		Baharyia	Shaley sand
Kharita	F	112	2275	391.77		Kharita	Shaley sand
Dahab	F	120	2666.77	79.26		Dahab	Shaley sand
Erosion 3	E	125			−100		
Alamein Ghost Layer	D	128			100	Dolomite	Dolomite
Alam El-Bueib	F	130	2746.03	301.83		Alam El-Bueib	Shaley sand
Betty	F	144	3047.86	88.42		Betty	Sandy shale
Erosion 2	E	150			−200		
M. Jurassic Ghost Layer	D	170			200	Limestone	Limestone
Eghi	F	286	3136.28	312.25		Eghi	Shaley sand
Erosion 1	E	300			−300		
Basement Ghost Layer	D	310			300	Shaley sand	Shaley sand
Basement	F	500	3448.53	47		Basement	Basement

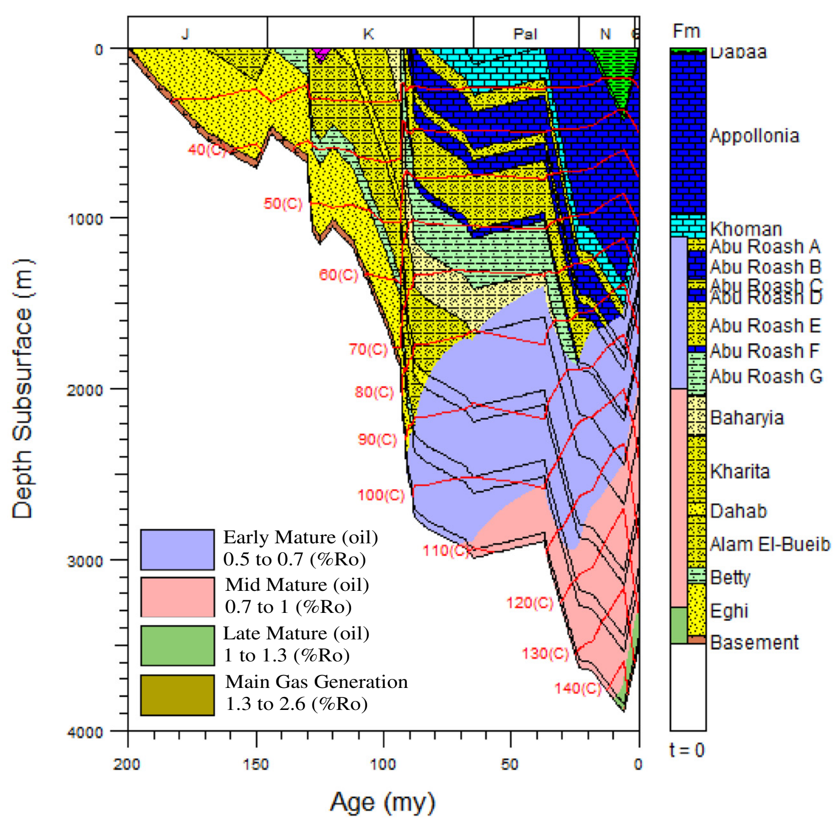

Figure 13 Burial history model with LLNL Easy %Ro maturity window of the Fayoum-1X well.

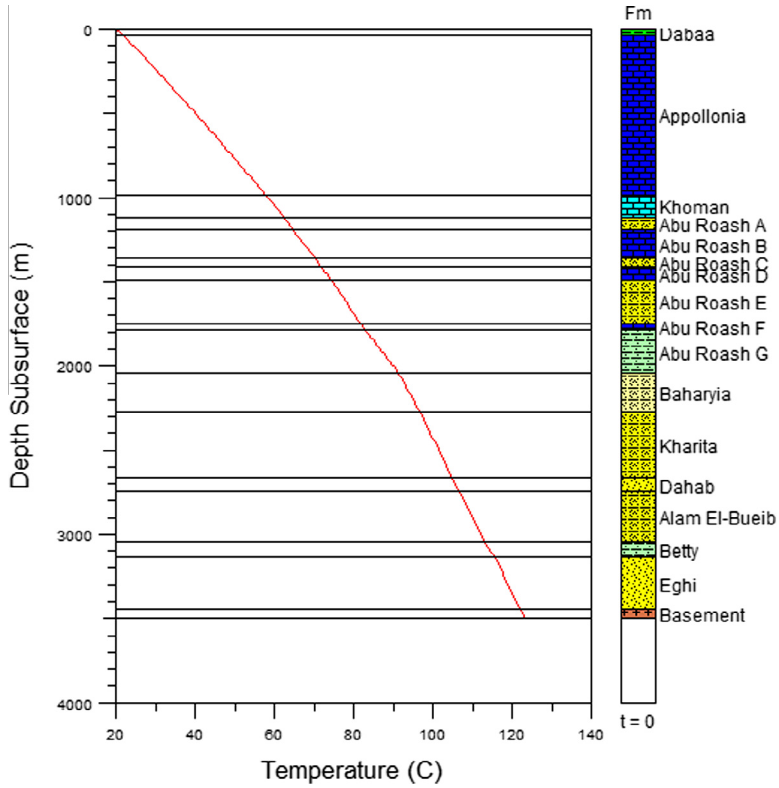

Figure 14 Relationship between formation temperature and depth of the Fayoum-1X well.

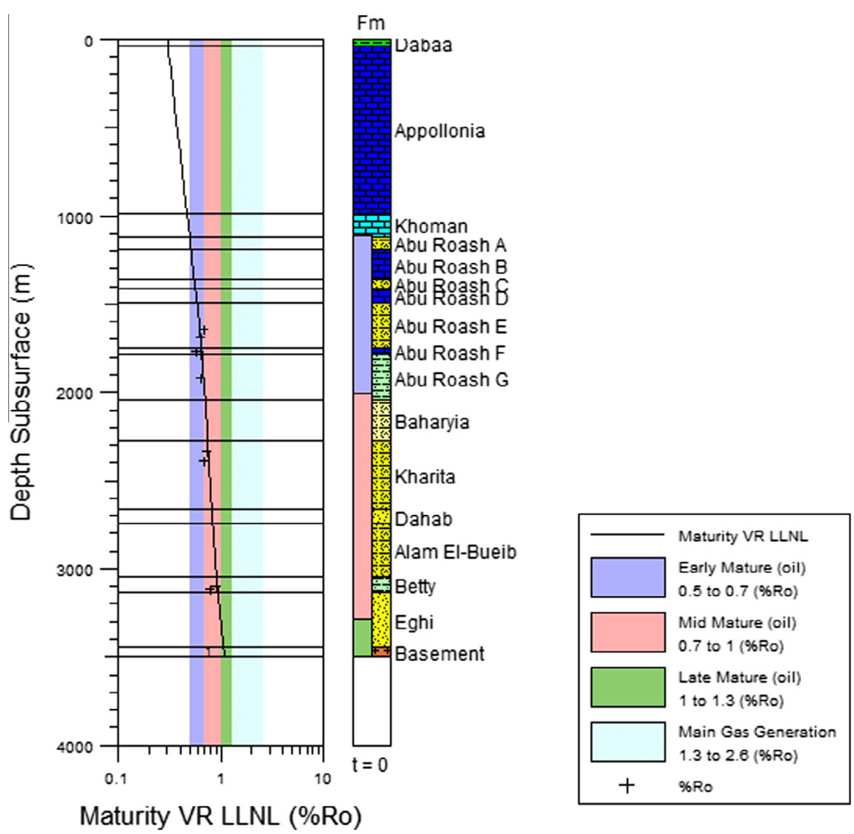

Figure 15 Calibration of maturity LLNL Easy %Ro with measured %Ro of the Fayoum-1X well.

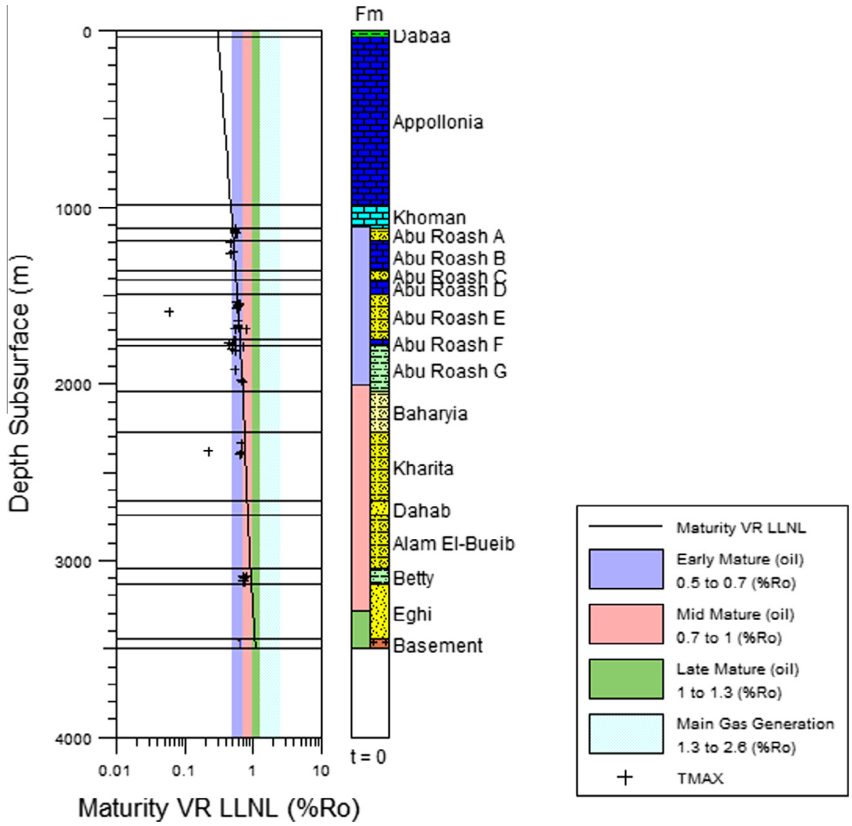

Figure 16 Calibration of maturity LLNL Easy %Ro with T_{max} of the Fayoum-1X well.

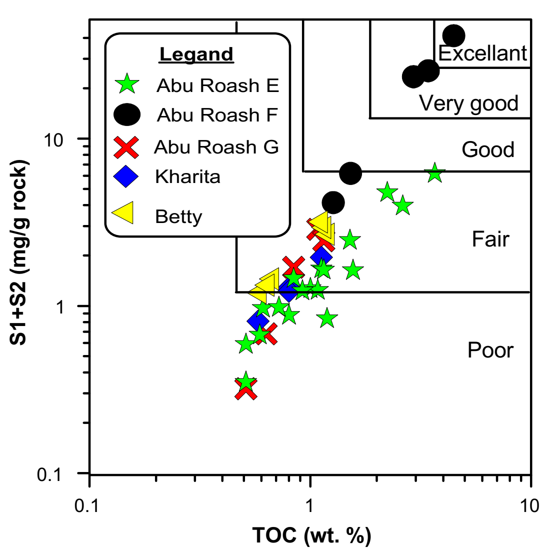

Figure 17 Generation potential of the Fayoum-1X well.

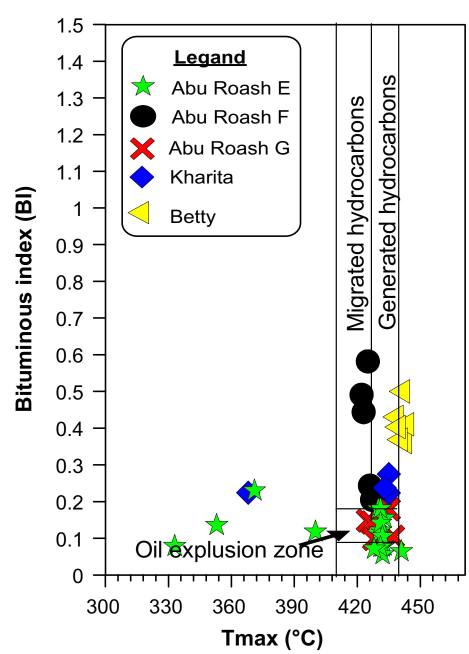

Figure 18 Expulsion potential of the Fayoum-1X well.

($S1$), and further increasing BI. The sharp increase in BI that occurs at a T_{max} of 430–440 °C (or corresponding to 0.54–0.73 %Ro) marks the onset of petroleum generation. At %Ro of 1.8%, $S1$ yields are very low, the threshold of petroleum generation was found at %Ro of 0.5–0.6% and build-up of liquid petroleum occurs between 0.5 and 0.85 %Ro [20,28,29]. In this work and according to the previous discussion, the hydrocarbons present in Abu Roash (F member) may be generated from the same rock or migrated from another source rock because most of the organic matter ranges from immature to margin of the mature stage (Fig. 18). But the hydrocarbons are mainly generated from Abu Roash (E and G members), Kharita and Betty formations (Fig. 18) due to the high level of maturation which reached to super maturation stage.

5. Conclusions

Rock-Eval pyrolysis data is used to determine the organic carbon richness, types of organic matter and thermal maturation level, and used well log data to determine the organic carbon richness for Abu Roash (E, F and G members), Kharita and Betty formations of the Cretaceous sequence in the Fayoum-1X well. BasinMod 1D software is used to construct the burial history model of Fayoum-1X well and to calculate the levels of thermal maturity based on calibration of measured %Ro and T_{max} against the LLNL Easy %Ro model.

In the studied well, oil prone source rock with excellent generation potential is encountered in Abu Roash (F member), whereas those with fair capacity to generate mainly oil with some gas is encountered within Abu Roash (E member). Mixed oil/gas prone rocks are represented by localized shale-rich intervals within Abu Roash (G member) and Betty Formation. Organically-rich sediments with very good capacity to generate mainly gas are encountered within the Kharita Formation.

The TOC calculations from $\Delta \log R$ technique, Density Log method of the well log data of the Fayoum-1X well give a good match with the measured TOC against shale source rocks, but gives high or low values against limestone source rocks. For that, a new derivative model is applied on limestone of Abu Roash (F member) source rock depending on PEF, ILD logs and V_{sh} gives a good match with the measured TOC of Fayoum-1X well.

Thermal maturation from the measured %Ro reflects that Abu Roash (E member) is a mature source rock, eventually, Abu Roash (F member) is an immature source rock, whereas Abu Roash (G member), Kharita and Betty formations range from the mature to super mature stage. The T_{max} and PI data indicate that Abu Roash (F member) is present on the margin of the maturation stage, whereas Abu Roash (E and G members), Kharita and Betty formations range from the immature to mature stage. So that, the thermal maturation must be determined by using more than thermal maturity indicators (T_{max}, PI and %Ro) and correlate between them to achieve more accurate results.

The expulsion potential indicates that hydrocarbons present in Abu Roash (F member) may be generated from the same source rock or migrated from another source rock, but the hydrocarbons in Abu Roash (E and G members), Betty and Kharita formations are mainly generated from inside the same source rock.

The burial history model of Fayoum-1X well with LLNL Easy %Ro maturity indicator reflects that Abu Roash (A–F and upper part of G members) reached the early mature stage, whereas the lower part of Abu Roash (G member), Baharyia, Kharita, Dahab, Alam El-Bueib, Betty formations reached the mid mature stage.

Appendix A

$R_{baseline}$ $\Delta t_{baseline}$	The values of the fine-grained non-source rocks chosen after superimposing the two logs
Δt	The sonic log value, μs/m
ρ	The density, gm/cm^3
I_{GR}	Gamma ray index
GR_{log}	Gamma ray reading of formation
GR_{min}	Minimum gamma ray (clean sand or carbonate)
GR_{max}	Maximum gamma ray (shale)

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